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Operation of YBCO current leads as bias lines to cryocooler-mounted 4 K superconducting electronics

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Abstract

We report on the construction and operation of flexible, 15-line YBCO lead assemblies as low heat-leak bias lines to a complex Rapid Single Flux Quantum (RSFQ) circuit on a 2-stage cryocooler. The leads are used to supply DC bias currents of about 30 mA per line to the circuitry operating at 4 K. They span the temperature difference between the 1st (~50 K) and 2nd (~4 K) stages of a Gifford-McMahon cryocooler, substantially cutting the heat load to the 2nd stage when compared to optimized normal metal leads. No measurable change in the temperature of the 4 K stage associated in Joule heating in the superconducting leads or end joints was observed when the full set of 24 bias lines was taken to operational current, and no degradation was observed after the cryocooler maintained temperature for six months. The leads are made by patterning 12 mm-wide 2G tape, the heat load of which is dominated by conduction through the cable's Hastelloy substrate. We have measured the thermal and electrical transport properties of the Hastelloy® substrate and believe that they are significantly changed by processing history.

Nomenclature

L_0	Lorenz constant (2.44×10^{-8} WΩ/K^2)
κ_e	electronic contribution to thermal conductivity
σ	electrical conductivity
T	temperature
Q	Rate of heat flow
I	current
k_B	Boltzmann's constant
e	electronic charge

Current leads;HTS;YBCO;cryocooler;RSFQ;superconducting electronics

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1. Introduction

The use of High Temperature Superconductors (HTS) as current leads for magnets wound from conventional Low Temperature Superconductors (LTS) has been well established as a means to substantially reduce the heat leak into the LTS magnet with corresponding savings of liquid helium (LHe) or reduced refrigeration load for cryocooled cryostats[1]. The leads are designed to carry currents anywhere from 100 A to several thousands; in our previous work[2],[3] we have been addressing the need for such thermal efficiency in the context of LTS electronic circuits, which require much smaller, but not insignificant DC biasing currents. In particular, Hypres has been developing a series of digital receiver systems using niobium Josephson junctions mounted on 4 K cryocoolers[4][5]; each chip operating at about 4 K requires 10s of parallel bias currents totaling about 1 A. No commercially available HTS leads are yet optimized to carry sub-1 A currents from, say, 80 K to 4 K; this work addresses the lack.

For the supply of current between two temperatures via *normal* metals a fundamental minimum net heat leak exists per unit current due to the opposing requirements of low Joule heating and low heat conduction[6]. If we consider only the electronic contribution to heat transport, the minimum net heat leak is governed by the Wiedemann-Fanz (W-F) rule (equ. 1) and becomes[7]:

$$\frac{Q}{I}_{min} \approx 3.6 k_B T_{hot}/e \qquad (1)$$

Our targeted application is a lead carrying an average of 35 mA and linking a 50 K stage to a 4 K stage with no intermediate cooling; the normal metal minimum heat leak would be 460 μW per line in this case. By this metric, we have demonstrated a 6-fold reduction in heat load with our patterned HTS leads

2. Fabrication of multi-line leads

SuperPower supplied tape with 100 μm-thick Hastelloy® substrate, a 1 μm-thick MgO buffer layer, a 1 μm-thick layer of YBCO and a 3 μm-thick layer of silver. 10 cm-long samples were etched by Superconductor Technologies Inc. by ion beam milling as described in 2 15 lines were produced on the 12 mm-wide tape, each line being 300 μm wide and with a pitch of 625 μm; the pitch was originally chosen to match surface-mount connectors. Line-to-line and line-to-substrate isolation was provided by the 1 μm-thick buffer layer and was typically 1 MΩ at liquid nitrogen temperature; careful ion-beam milling was necessary to avoid etching through the buffer layer between lines. The end 1 cm of each line was left covered with the original silver for ease of joint fabrication, and between the regions of silver, the tape was covered by a coating of DuPont Teflon AF®. Typical critical currents (I_c) measured were ~3 A in liquid nitrogen which represents about 80% of the bulk critical current density of the as-manufactured tape (see fig. 1). Attempts were also made to fabricate similar leads with tape, which has a buffer layer of only 0.1 μm thickness, however it proved too difficult to maintain adequate electrical isolation from the substrate during the integration with input and output leads and so thin buffer layer tapes were not pursued further.

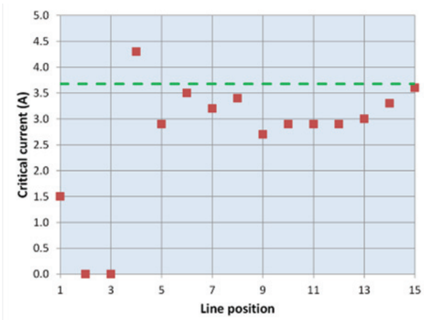

Fig. 1 Critical currents of patterned 300 μm lines on 10 cm-long,12 mm-wide YBCO tape sample, measured in liquid nitrogen (surface mount connectors at each end). The dashed line represents the critical current of the unpatterned tape proportioned to the line width.

3. End Joints

3.1 Surface-mount connectors

As mentioned above, the pattern was chosen to match a particular miniature surface mount connector and we experimented with direct soldering of them to the silver coated lines. Although we were able to make functional cables this way, they suffered from 2 major drawbacks:

(i) The strength of adhesion between the silver and YBCO or the YBCO and buffer layer was not sufficient to prevent breakage after multiple cool-downs and the vibrations from the cryocooler even when epoxy encapsulation was applied after soldering.

(ii) Multi-pin connectors (Omnetics) with a 0.625 mm pitch have a typical resistance of 15 mΩ per line, which leads to an unacceptably high amount of Joule heating at the cold end (4 K) with a typical operating current of 35 mA, i.e. 18 μW per line.

This direct "connectorization" of the leads was therefore dropped in favor of a lap-joint approach.

3.2 Compression lap-joints

A lap-joint was formed between a copper-on-Kapton® flex PCB and the patterned YBCO tape by inserting both into a copper clamp; the clamp served to align the conductors, provide a compressive clamping force, provide direct heat-sinking at the joint to a cryocooler stage as well as a mechanical anchoring point as shown in fig. 2. The clamping force is provided by 2 screws with spring washers and proved to be remarkably robust. At liquid nitrogen temperature the 60 joints from a pair of 15-line cables were all measured at <0.5mΩ. At the 4 K end, the copper/Kapton flex PCB was soldered via an FR-4 PCB to a larger connector with lower resistance than the surface-mount connectors.

4. Thermal conductivity of Hastelloy® substrate

4.1 Measurement technique

The thermal conductance of the leads without their silver coating is dominated by the contribution from the substrate 2, so careful measurement of it was required. Figure 3a shows our set-up for measuring the thermal conductivity of the Hastelloy® tape. Each sample was soldered to copper blocks to achieve excellent thermal contact; in steady state, the heater power into the floating end of the sample is proportional to the thermal conductivity integral, the conductivity itself was derived by differentiation. Since the tape is so thin, the sample aspect ratio was chosen to maximize its conductance so that it dominated the parasitic conductances. The whole was mounted to the second stage of a 4 K Gifford-McMahon cryocooler in an evacuated cryostat.

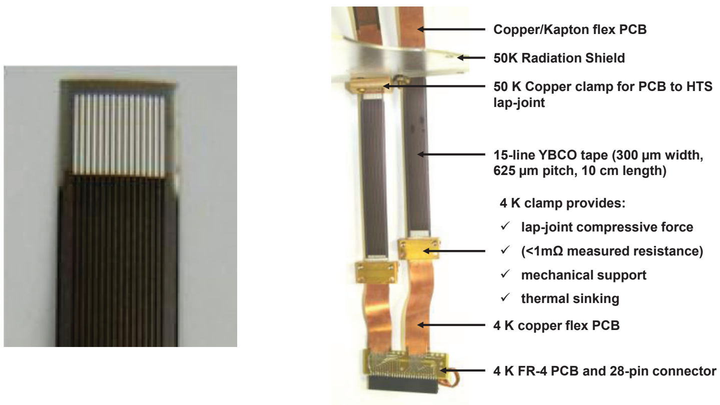

Figure 2 a) Patterned 12 mm tape b) Cable assembly with clamped joints to flexible 15-line PCBs

4.2 Discussion of results

As can be seen from fig. 3b, we find the surprising result that the thermal conductivity of the Hastelloy® tape is suppressed by the act of manufacture into YBCO composite cable by nearly a factor of two in the range of interest. Yamada et al [8] measure a very similar set of values to our results for the post-processing tape, whereas Lu et al 9 show results closer to our raw Hastelloy measurements. We speculate that during the oxygen annealing of the YBCO, oxygen penetrates the full thickness of the tape and oxidizes the surfaces of Hastelloy® grains, so increasing the inter-granular thermal resistance. This is consistent with our room temperature measurements of the electrical resistivity, the results of which are:

Lu et al data, 100 μm thick tape	1.25 μΩ-m
Raw C-276 tape from SuperPower (Hypres measurement)	1.25 μΩ-m
Post-manufacture and coating removal (Hypres measurement)	1.84 μΩ-m

By applying the W-F rule to the electrical resistivity as per equation 2, the electronic contribution to the thermal conductivity was calculated and shown in fig. 3b; clearly the drop in conductivity caused by the YBCO processing is not solely as a result of the change in the electronic contribution, but the phononic transport of heat is also greatly affected.

$$L_0 = \frac{\kappa_e}{\sigma T} \tag{2}$$

Using our data for the substrate post processing, we calculate that the leads contribute 16% of the heat load of idealized normal metal leads; if we took into account that the leads can carry much higher currents than 35 mA, the factor would be much higher. Nonetheless, the heat load reduction can easily be improved further by reducing the line pitch and using a 50 μm-thick substrate (readily available).

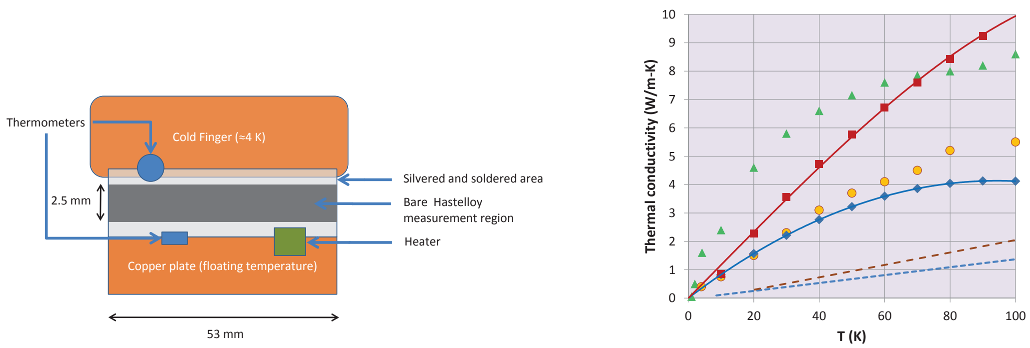

Fig. 3 a) Schematic diagram of thermal conductivity measurement apparatus. b) Thermal conductivity versus temperature for Hastelloy® tape substrates. The four sets of data shown are: ◆ 50 μm-thick sample supplied by SuperPower, Inc. originally composite conductor, then stripped of Ag, YBCO and buffer layer and measured by Hypres; ▲ data from Lu et al [9] for C-276 Hastelloy® 100 μm-thick; ■ virgin C-276 tape supplied by SuperPower, Inc.; ○ data from Yamada et al 8 on 100 μm-thick C-276 sample. The dashed lines are calculated electronic contribution to thermal conductivity using the W-F rule for – – unprocessed tape measured at Hypres, - - - processed tape stripped of coatings and measured at Hypres.

5. Cable testing on 4 K cryocooled electronics system

As one of the preliminary cryocooled tests, a single cable was installed on the cryocooler spanning the two stages and shorted at the 4 K stage; 700 mA was fed to each line simultaneously for several hours during which time all the lines remained superconducting and temperatures stabilized.

The pair of 15-line cables shown in figure 2 was installed on a cryostat centered on a 100 mW (@4.2 K) Sumitomo cryocooler which supported the operation of a niobium-based Rapid Single Flux Quantum (RSFQ) analog-to-digital converter [10]circuit. 24 separate bias lines (average 35 mA per line) supplied a total of 600 mA to the ADC, all of them adiabatically spanning the 2 stages (50 K to 4 K) via the YBCO cables. The chip was biased and operated without any detectable heating (<1 mK temperature rise) from the YBCO cables or the end joints; the expected small amount of heating that was observed was due to the bias resistors of the RSFQ chip itself.

The cryostat was kept at operating temperature for 6 months except for a few warm-up and cool-down cycles and at the end of this the chip was biased again with the same results: all biases were operational with only Joule heating from the chip itself.

6. Conclusions

We have designed and fabricated a 15-line current lead assembly from commercially available 2G YBCO tape which delivers currents of about 35 mA between 50 K and 4 K thermal stations in vacuo with only 1/6 of the heat transport of optimized normal metal leads. Given that the lines will carry at least 700 mA under these conditions, future designs could reduce the heat leak by another large factor. Two lead assemblies using clamped lap-joints to the YBCO were installed into a cryostat and supplied the total of 0.6 A biasing current via 24 lines necessary to operate a complex RSFQ chip at 4 K. No Joule heating from the leads was seen and no degradation after 6 months of cryocooler operation.

The thermal conductance of the leads is dominated by the Hastelloy® substrate which was found to have a thermal conductivity of about ½ that of virgin material; the manufacturing process of the composite conductor appears to suppress both its electrical and thermal conductivity. We suspect that oxygen annealing causes this change and suggest that metallurgical studies of this process would be illuminating.

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